

METHOD AND APPARATUS FOR THE TEMPERATURE COMPENSATION OF WRITE CURRENT AND WRITE CURRENT BOOST

CROSS REFERENCE TO RELATED APPLICATIONS

5 Priority is claimed from U.S. Patent Application Serial No. 60/257,133 filed
December 20, 2000, entitled "TEMPERATURE COMPENSATION FOR WRITE
CURRENT AND WRITE CURRENT BOOST", the disclosure of which is incorporated
herein by reference in its entirety.

FIELD OF THE INVENTION

10 The present invention relates to adjusting the write current and write current boost
in a hard disk drive in response to changes in temperature. In particular, the present
invention relates to preventing pole tip protrusion and write induced instabilities as a
result of elevated temperatures in combination with excessive amounts of write current
and write current boost.

15 BACKGROUND OF THE INVENTION

20 Hard disk drives are used to store large amounts of digital data. Typically, the
data is stored on magnetic storage disks in concentric tracks. The data tracks are usually
divided into sectors. Information is written to and read from a disk by a transducer head.
The transducer head may include a read head separate from a write head, or the read and
write heads may be integrated into a single read/write head. The transducer head is
mounted on an actuator arm capable of moving the transducer head radially over the disk.
Accordingly, the movement of the actuator arm allows the transducer head to access
different data tracks. The disk is rotated by a spindle at a high speed, allowing the
transducer head to access different sectors within each track on the disk.

Various parameters of the performance of a hard disk drive are dependent, at least in part, on temperature. For example, the amount of write current required to sufficiently magnetize the storage disk such that data is reliably encoded increases as the temperature of the disk drive decreases. The need for an increased write current at reduced

5 temperatures is the result of various factors. For instance, the coercivity of the magnetic storage disk, and thus the strength of the field required to encode a pattern of magnetization on the disk, increases as the temperature of the magnetic media of the storage disk decreases. In addition, the flying height of the transducer head over the surface of the magnetic disk increases as the temperature decreases and the density of the

10 air inside the disk drive increases. A higher flying height generally requires a larger write current due to the increased distance between the transducer head and the surface of the magnetic disk.

At elevated temperatures, the amount of write current required to encode data on the magnetic storage disk decreases. In part, this is because the coercivity of the magnetic storage media decreases as temperature increases. Therefore, a lesser magnetic field strength, and thus a lower write current, is required to encode data on the magnetic disk.

15 In addition, the flying height of the transducer head at elevated temperatures is generally lower, because the air is less dense, placing the transducer head in closer proximity to the magnetic media.

20 In order to provide a write current that is operative in most situations, the designers of hard disk drives have attempted to choose a write current amount that is satisfactory over a variety of anticipated operating temperatures. Other methods for

avoiding problems due to inappropriate write current amounts include screening transducer heads to eliminate those with a poor writer (*i.e.* write heads requiring large amounts of current), and restricting the operating temperature range of the disk drive. However, as the data storage densities and data transfer rates of hard disk drives have increased, the ability of hard disk drives to tolerate variations in written data has decreased. It is known in the art to vary the amount of write current or write current boost based on the zone on the disk in which the write is to occur. However, such variation is adapted to the different data frequencies used in different zones. Therefore, in order to ensure that data is written consistently, a need has emerged to vary the amount of write current used to encode data in response to changes in temperature.

Attempts have been made to vary write current amounts with temperature to maintain a desired track width, because changes in the coercivity and/or flying height of the transducer head results in data tracks having varying widths. However, in conventional disk drives the amplitude of write current boost has not been adjusted in response to temperature. In addition, conventional disk drives have neglected to consider other problems that may result from write current amounts that are inappropriate for a given temperature.

As an example, deformation of the transducer head may occur due to a combination of elevated ambient temperatures and high write currents and write current boosts. Such deformations may include pole tip protrusion, in which the transducer head protrudes from the surface of the slider. In such a condition, the transducer head is more likely to come into contact with the storage media, both because of the protruding

transducer head and because the flying height of the transducer head is lower at elevated temperatures, when pole tip protrusion is more likely to occur. Contact between the transducer head and the storage media can damage the storage media and the transducer head. In addition, such contact can result in positioning errors and increases in the data error rate of the hard disk drive. However, existing systems have generally not considered pole tip protrusion in determining appropriate amounts of write current.

As a further example, too high a write current and/or too high a write current boost for the temperature of the transducer head can cause instabilities in the transducer head. Such instabilities can lead to a temporary or even a permanent inability of the transducer head to reliably and accurately read and/or write data. In particular, an excessive write current and/or write current boost can cause write induced instabilities in the read head due to pinning of the magnetic domains in the read head, causing the read head to be insensitive to the magnetic fields associated with encoded data. Further, as areal densities have increased, transducer heads have become narrower, increasing their sensitivity to write induced instabilities.

SUMMARY OF THE INVENTION

In accordance with the present invention, temperature compensation for write current and write current boost is provided. In particular, the present invention provides temperature compensation for write current and write current boost in order to prevent deformation of the transducer head and to prevent write induced instabilities, thereby helping to ensure that data can be reliably stored and retrieved.

In accordance with an embodiment of the present invention, a write current and a write current boost that provide the desired write characteristics are determined for a hard disk drive at a first temperature. In general, the write current and write current boost should be chosen to reliably encode data on a magnetic disk, without causing deformation of the transducer head, and without causing write induced instabilities. Deformation may occur when a transducer head is overheated due to large write current and/or write current boost amounts at high ambient temperatures. Write induced instabilities occur when magnetic domains in the transducer head are pinned by high write current and/or write current boost amounts, causing the read element to become insensitive to data. In general, the write current and write current boost must be sufficiently strong to encode data to the magnetic storage disk such that the data can later be reliably retrieved. Deformation of the transducer head and write induced instabilities may be detected by monitoring a position error signal and/or a mean square error associated with the transducer head. A sudden change in the position error signal indicates that the transducer head has deformed, and in particular that the pole tip has protruded, due to heating from excessive write current and/or write current boost, and/or that the transducer head is experiencing write induced instabilities. Similarly, a sudden change in the mean square error of data written with the transducer head indicates a deformation of that transducer head due to heating from excessive write current and/or write current boost. Instabilities can be detected by determining whether an error is indicated while attempting to read servo sector address data.

In accordance with an embodiment of the present invention, a disk drive storage device having a temperature sensor is provided. The temperature sensor may be a discrete component located within or on the disk drive, or may be provided as an additional function of some other component located within or on the disk drive. For example, the temperature sensor may be provided as part of the read/write channel or the preamplifier of the disk drive. Using the temperature sensor, the ambient temperature of the disk drive is determined. The amount of write current and write current boost for a particular zone of the storage disk addressed by the particular transducer head performing a write operation is obtained from a table of write currents and write current boosts maintained in memory. The amount of write current and write current boost actually provided to the transducer head is then determined according to the observed ambient temperature of the disk drive. The temperature compensation of current amounts ensures that pole tip protrusion does not occur, even at elevated ambient temperatures, thereby avoiding contact between the transducer head and the storage disk. The temperature compensation of current amounts may also ensure that write induced instabilities do not occur in the read head. In addition, the write current and write current boost amounts may be modified to ensure that a sufficient write current and write current boost are available at reduced ambient temperatures. According to still another embodiment of the present invention, a table of write currents and write current boosts may be maintained to provide an appropriate current to a transducer head for a given temperature range. According to an embodiment of the present invention, write current and write current boost may be optimized for each transducer head included in a disk drive.

Additional advantages of the present invention will become readily apparent from the following discussion, particularly when taken together with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

5 **Fig. 1** is a diagrammatic representation of a top view of a conventional computer disk drive, with the cover removed;

Fig. 2 is a diagrammatic representation of an air bearing slider incorporating a transducer head;

10 **Fig. 3** depicts a cross section of a transducer head having integrated read and write heads;

Fig. 4 is a plan view of the transducer head of **Fig. 3**;

Fig. 5A depicts the relationship between a transducer head and the surface of a magnetic disk during normal operation;

15 **Fig. 5B** depicts the relationship between a transducer head and the surface of a magnetic disk at elevated temperatures in accordance with the prior art;

Fig. 5C depicts the relationship between a transducer head and the surface of a magnetic disk at elevated temperatures in accordance with an embodiment of the present invention;

20 **Fig. 6** is a flow chart depicting the determination of a write current and a write current boost in view of the observed bit error rate in accordance with an embodiment of the present invention;

Fig. 7 is a flow chart depicting the determination of a write current and a write current boost in view of various types of position errors in accordance with an embodiment of the present invention; and

Fig. 8 is a flow chart depicting the operation of a disk drive in accordance with an embodiment of the present invention.

DETAILED DESCRIPTION

Fig. 1 illustrates a typical disk drive, with the top cover removed. The disk drive, generally identified by reference number **100**, includes a base **104** and magnetic disks **108** (only one of which is shown in **Fig. 1**). The magnetic disks **108** are interconnected to the base **104** by a spindle motor (not shown) mounted on or beneath the hub **112**, such that the disks **108** can be rotated relative to the base **104**. Actuator arm assemblies **116** (only one of which is shown in **Fig. 1**) are interconnected to the base **104** by a bearing **120**. The actuator arm assemblies **116** include transducer heads **124** (only one of which is illustrated in **Fig. 1**) at a first end, to address each of the surfaces of the magnetic disks **108**. An actuator **128**, such as a voice coil motor, pivots the actuator arm assemblies **116** about the bearing **120** to radially position the transducer heads **124** with respect to the magnetic disks **108**. The actuator **128** is operated by a controller **132** that is in turn operatively connected to a host computer (not shown). By changing the radial position of the transducer heads **124** with respect to the magnetic disks **108**, the transducer heads can access different data tracks or cylinders **136** on the magnetic disks **108**. A read/write channel **140** processes data signals written to or read from the disks **108**, and a

preamplifier 144 provides write signals to the transducer heads 124. In addition, the disk drive 100 may include a temperature sensor 148, located within or on the disk drive 100.

With reference now to Fig. 2, a transducer head 124 incorporating an integrated read/write head 204 and an air bearing or slider 208 is illustrated. In general, the air bearing 208 supports the transducer head 124 on a layer of air created by the spinning of the disk 108 when the disk drive 100 is in operation.

With reference now to Fig. 3, an integrated read/write head 204 is shown in cross section. The read/write head 204 generally includes a write head or element 304 and a read head or element 308.

The write head 304 may be what is known as an inductive head. The write head 304 generally includes a yoke 310 of magnetically conductive material formed from a write pole 312 and a shared shield 316. A coil 318 of electrically conductive wire is wrapped about a portion of the yoke 310, and the ends of that coil 318 are connected to a current source (not shown). During a write operation, current is introduced to the coil 318 in a first direction. The electrical current through the coil 318 produces a magnetic field within the yoke 310. At a gap 320 formed between an end of the write pole 312 and an end of the shared shield 316, the magnetic field spreads out because the magnetic permeability of the gap 320 is less than that of the yoke 310 itself. The gap 320 is positioned so that it is in close proximity to the magnetic disk 108, allowing some of the magnetic field to pass through the disk 108 and magnetize a portion of the disk 108 in a particular direction. In a typical disk drive 100 for use in a digital computer, a "1" is coded by reversing the direction in which the disk 108 is magnetized from one portion of

the track 136 to the next. This is done by reversing the direction of the current in the coil 318. A "0" is indicated by the absence of a change in magnetic polarity. Of course, these conventions could be reversed.

The write current supplied to the conductive wire forming the coil 318 is generally in the form a square wave. The amount of current provided during a write operation is, according to the present invention, varied depending on the ambient temperature of the disk drive 100. In particular, because the write current supplied to the coil 318 heats the write pole 312 and the shared shield 316, those elements and the surrounding material of the transducer head 124 expand during write operations. When expansion is large, it is know as pole tip protrusion. Pole tip protrusion increases the likelihood that the write pole 312, the shared shield 316 and other areas of the transducer head 124 will come into contact with the surface of the disk 108, causing errors. In addition, when the ambient temperature of the disk drive 100 is high, the write pole 312 and shared shield 316, together with the other portions of the read/write head 204 are in closer proximity to the surface of the disk 108 because the flying height of the transducer head 124 itself is lower. The lower flying height of the transducer head 124 is due to a decrease in the density of the air inside the disk drive 100 at elevated temperatures.

The write current boost applied to the coil 318 during write operations also has the effect of heating the write pole 312 and the shared shield 316 and potentially causing pole tip protrusion. Consequently, according to the present invention, both the write current and the write current boost may be adjusted according to temperature. The write current boost is generally applied as a current component having a relatively high amplitude and

short duration, and is timed to coincide with the leading edge of the square wave comprising the write current itself. The write current boost is of particular importance in connection with data written at high frequencies, as the duration of the square pulse of the write current is short, and thus the write current boost makes up a larger proportion of the write signal. In addition, it is important to control the magnitude of the write current boost, as its relatively high amplitude can significantly heat, and thus expand, the read/write head 304.

The read head 308 operates by sensing the magnetic flux transitions encoded in the disk 108 by the write operation. One method of sensing such transitions is with a magnetoresistive head. Such a head is comprised of material that changes its electrical resistance when it is exposed to a magnetic field. Magnetoresistive heads have come into wide use in disk drive systems because they are capable of providing a high output signal. A high signal output is important, because the magnetic fields produced in the disks 108 by the write operation are very small. In addition, the high signal output of the magnetoresistive head allows the data on the disk to be densely packed, in turn allowing the disk drive 100 to have a high storage capacity.

Magnetoresistive heads generally include a strip of magnetoresistive material 324 held between two magnetic shields. In the integrated read/write head 204 illustrated in Fig. 3, the magnetic shields are formed from the shared shield 316 and a read shield 328. Each end of the strip of magnetoresistive material 324 is connected to a conductor (not shown). The conductors are in turn connected to a current source (not shown). Because the electrical resistance of the magnetoresistive material 324 varies with the strength and

direction of an applied magnetic field, magnetic flux transitions result in changes in the voltage drop across the magnetoresistive strip **324**. These changes in the voltage drop are then converted into a digital signal for use by the disk drive controller **132** and in turn the host computer.

5 The read head **308** is sensitive to changes in the magnetic domains of associated components, such as the shared shield **316**, which can occur during write operations. Such changes can momentarily, or even permanently, render the read head **308** ineffectual. In particular, the magnetic domains can be pinned in a particular direction, causing the read head **308** to become insensitive. Therefore, it is important that the write current and write current boost supplied to the coil **318** during write operations is not
10 higher than necessary to adequately write data to the disk **108**. In addition, it is particularly important to limit the amount of the write current and write current boost supplied to the coil **318** when the ambient temperature of the disk drive **100** is elevated. This is because the read head **308** is particularly vulnerable to insensitivity caused by high
15 write currents and write current boosts when the ambient temperature of the disk drive **100** is elevated. This is believed to be due to the relative ease at which the magnetic domains within the shared shield **316** and other components of the read/write head **204** can be altered at elevated temperatures.

 With reference now to **Fig. 4**, a typical read/write head **204** is shown in plan view.
20 As described above, the write head **304** generally includes a write pole **312** and a shared shield or pole **316**, with a write gap **320** therebetween. The read head **308** generally

includes the shared shield **316**, a magnetoresistive element **324**, and a read shield **328**.

Such heads are typically manufactured using thin film layering techniques.

With reference now to **Fig. 5A**, a transducer head **124** is shown in partial cross-section, operatively positioned over the surface of a magnetic disk **108**. In particular, **Fig. 5A** shows the flying height h_1 of the slider **208** over the surface of the magnetic disk **108**. Also illustrated in **Fig. 5A** is the distance d_1 between the tip of the write pole **312** and the surface of the magnetic disk **108**. In general, it is important to accurately maintain the desired fly height d_1 over the surface of the disk **108** so that data can be reliably written to and retrieved from the magnetic disk **108** by the read/write head **204**. This in turn requires that the distance h_1 be accurately controlled.

With reference now to **Fig. 5B**, the effects of elevated temperatures on the flying height h_2 and the contour of a conventional read/write head **204** is illustrated. In particular, it will be noted that the flying height h_2 is decreased as compared to the flying height h_1 (see **Fig. 5A**). This is because the ambient temperature inside the disk drive **100** in **Fig. 5B** is higher than in **Fig. 5A**, and at elevated temperatures the density of air decreases, thereby decreasing the pressure applied to the slider **208** and in turn decreasing the flying height h_2 . In addition, **Fig. 5B** illustrates a condition in which the transducer head **124** is experiencing pole tip protrusion. In particular, it will be noted that various of the elements of the read/write head **204** and at least the immediately adjacent area of the slider **208** have expanded beyond the normal contour of the slider **208**, represented by dotted line **504b**. This condition is known as pole tip protrusion, and is typically caused by a combination of elevated ambient temperatures within the disk drive **100**, and elevated

temperatures within the read/write head **204** itself due to high write currents and/or write current boosts. The combination of a decreased fly height h_2 and pole tip protrusion results in a distance d_2 between the surfaces of the read/write head **204**, such as the tip of the write pole **312**, and the surface of a magnetic disk **108** that is relatively small.

5 Accordingly, the read/write head **204** is more likely to contact the surface of the disk **108**, causing positioning errors, and potentially damaging the surface of the disk **108**. In addition, contact between the read/write head **204** and the surface of the disk **108** can dislodge particles, potentially causing damage to other portions of the disk **108**, or to other components within the disk drive **100**.

10 With reference now to **Fig. 5C**, the relationship between a transducer head **124** and the surface of a magnetic disk **108** at the same elevated temperature as the example in **Fig. 5B**, in accordance with an embodiment of the present invention is illustrated. Of particular note is the fly height h_3 of the slider **208** above the surface of the disk **108**. Specifically, the fly height h_3 is equal to the fly height h_2 shown in the prior art transducer head **124** illustrated in **Fig. 5B**. However, it will be noted that the surfaces of the read/write head **204**, such as the tip of the write pole **312** in the embodiment illustrated in **Fig. 5C**, does not extend beyond the plane defining the lower extent of the slider **208**, shown by dotted line **504c**. This is because, according to the present invention, the amplitude of the write current and of the write current boost has been decreased to
15 compensate for the elevated ambient temperature of the disk drive **100** in the example of **Fig. 5C**. Therefore, at the same elevated ambient temperature, the distance d_3 between the tip of the write pole **312** and the surface of the disk **108** in the disk drive **100** in
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accordance with the present invention is greater than the distance d_2 in connection with the example of **Fig. 5B** illustrating a transducer head assembly **124** in accordance with the prior art. Accordingly, damage and/or reduced disk drive **100** performance due to contact between the write pole **312** and the surface of the disk **108** is less likely to occur in connection with a disk drive **100** in accordance with the present invention. Also, because the present invention provides a reduced write current and write current boost at elevated ambient temperatures, instabilities in the read head **308** are less likely to occur in a disk drive **100** in accordance with the present invention than in the prior art device. Furthermore, as described below, the amount of write current and write current boost are also controlled in accordance with the present invention to reduce or eliminate write induced instabilities in the read head **308**.

In determining an appropriate write current and write current boost, several factors must be considered. In particular, the write current and write current boost should be strong enough to produce a magnetic field capable of producing the desired magnetization of the magnetic disk **108**. In particular, the magnetization of the magnetic disk **108** should be sufficiently strong to later allow for the reliable retrieval of data encoded on the disk **108**. However, the write current and write current boosts should not be so great that the magnetic field produced at the gap **320** of the write head **304** overrides data in tracks adjacent to the target track. In general, a nominal write current and write current boost is determined for each transducer head **124** included in a disk drive **100**. Alternatively, a nominal write current or write current boost may be determined for less than all of the transducer heads **124** in a disk drive **100** during optimization of the disk drive **100**. The

optimization process may be performed prior to delivery of the disk drive **100** to the end user. Various combinations of write current and write current boost may be used to write test sequences of data, as will be explained in greater detail below. The levels of write current and write current boost available may be predetermined. For example, a digital to analog converter or converters included as part of the preamplifier **144** of the disk drive **100** may be capable of providing a predetermined number of available output levels.

In addition to determining whether adjacent tracks are overwritten by a selected write current and write current boost combination, according to the present invention, additional aspects of the quality of the write process are considered. For example, the occurrence of pole tip protrusion may be detected by determining whether servo sector position bursts indicate that the transducer head **124** has suddenly changed position relative to the center line of the target track **136**. Furthermore, whether instabilities have been created in the transducer head **124** can be assessed by determining whether servo sector address data can be read following the writing of a test sequence of data.

The write current and write current boost determined during the optimization of an individual disk drive **100** may be stored in a table of write currents and write boost currents accessed by the disk drive **100** when write operations in connection with a particular transducer head **124** are performed. According to an embodiment of the present invention, the nominal write current and write current boost for a transducer head **124** is altered according to an algorithm when the observed ambient temperature of the disk drive **100** falls outside of a range of temperatures about the temperature at which the nominal write current and write boost current is determined. The determination of

appropriate algorithms for modifying the write current and write boost current due to changes in temperature will be described in greater detail below. According to another embodiment of the present invention, a write current and a write boost current for each of a plurality of temperature ranges may be stored in a table for each transducer head **124**.

5 With reference now to **Fig. 6**, a flow chart illustrating the determination of an appropriate write current and/or write current boost based on a desired track width in accordance with an embodiment of the present invention is depicted. Initially, at step **600**, the ambient temperature of the hard disk drive **100** is measured. The temperature measurement may be taken from a temperature sensor provided as part of another
10 component in the disk drive **100**, such as the read/write channel **140**, the preamplifier **144** or the controller **132**, or by a temperature sensor or transducer **148** separately provided as part of the disk drive **100** and located within a cavity **152** (see **Fig. 1**) enclosing the disks **108** and actuator arm assemblies **116**. As an alternative to sensing the ambient temperature within the cavity **152** of the disk drive **100** directly, it should be appreciated
15 that the temperature measurement may be taken from a sensor (e.g., temperature sensor **148**) located outside of the cavity enclosing the magnetic disks **108** and the actuator arm assemblies **116**. According to still another embodiment of the present invention, the temperature measurement may be taken from a location on a surface of the exterior of the disk drive **100**. The write current i may then be set at a first level, here denoted level 0.
20 The write current boost j may also be set a first level, here also denoted as level 0 (step **604**). In accordance with an embodiment of the present invention, the number of write current and write current boost levels available is dependent on the digital to analog

converter or converters included as part of the read/write channel 140 or the preamplifier 144. For example, in accordance with an embodiment of the present invention, 32 different write current levels are available from the preamplifier 144, and 8 different write current boost levels are available. According to this example, $8 \times 32 = 256$ different write current and write current boost combinations are available.

At step 608, a test sequence is written to at least a portion of a first track 136, and to corresponding portions of each of the two adjacent tracks. The quality of the data written to the initial track is then assessed. For example, the bit error rate associated with the test sequence written to the first track 136 is determined (step 612). An excessive bit error rate will result if the write current and/or write boost current used to write the data to the two tracks adjacent to the first track is too high. This is because the strength of the magnetic field produced in the read head 304 is too strong, and the widths of the adjacent tracks are therefore too great, causing the sequence of test data in the first track to be at least partially overwritten.

At step 616, a determination is made as to whether the measured bit error rate exceeds a specified value. If the measured bit error rate is within specified levels, a determination is made as to whether the write boost current j is equal to a maximum value (step 620). If j is not equal to a maximum value, the write current boost j is set equal to $j + 1$ (*i.e.* the write current boost is increased by one level) (step 624). If j is equal to a maximum value, the write current i is set equal to $i + 1$ (*i.e.* the write current is increased by one level), and j is set equal to an initial value, here 0 (step 628). After

either step 624 or 628 has been performed, the system returns to step 608, and a new test sequence is written to a first track and the two adjacent tracks.

If at step 616 it is determined that the measured bit error rate exceeds specifications, a determination is next made as to whether the write boost current is equal to a minimum value (here, value 0) (step 632). If the write current boost is equal to a minimum value, the write current i is set equal to $i - 2$ (*i.e.* the write current is reduced by two levels), and the write current boost j is set equal to a maximum value (step 636). If the write current boost j is not equal to a minimum value, the write current is set equal to i (*i.e.* it is left at its present value) and the write current boost j is set equal to $j - 2$ (*i.e.* the write current boost is reduced by two levels) (step 640). After completion of either step 636 or 640, the system returns to step 608, and a test sequence is again written to a first track and the two adjacent tracks.

It should be noted that the initial values for the write current i and the write current boost j set at step 604 need not be minimum values. For example, the initial values may be set at some intermediate level. This is particularly true when the temperature of the disk drive 100 during such testing is less than a design maximum temperature. Furthermore, it should be appreciated that the adjustments to the levels described in connection with Fig. 6 are examples only, and that changes by different amounts may appropriately be used.

With reference now to Fig. 7, a flow chart illustrating the optimization of a hard disk drive 100 based on the avoidance of pole tip protrusion and write induced instabilities is illustrated. Initially, at step 700, a second test sequence is written to a track

136 at the write current *i* and write current boost *j* determined during initial testing (*e.g.*, determined using the steps set forth in Fig. 6). The test sequence should be written to a relatively long segment of track 136, to produce heating of the transducer head 124, such as may occur during the writing of large amounts of user data. Therefore, according to one embodiment of the present invention, a test sequence is written to multiple data sectors. At step 704, a determination is made as to whether an error in reading servo sector position data is indicated, immediately following the step of writing the test sequence. If an error in reading the servo sector position information is encountered, write induced instabilities are indicated. This is because write induced instabilities cause the read head 308 to become insensitive to data stored on the magnetic disk 108. Accordingly, if write induced instabilities are present, the gray code used to encode servo sector position information in the servo sector encountered following the data sector to which the test sequence was written, will be unreadable. Accordingly, if an error reading the servo sector position information is encountered, the write current and/or write current boost should be decreased.

If no error is indicated in reading the servo sector position data, a determination is made as to whether an abrupt change in the position error signal has been detected (step 708). In general, an abrupt change in the position error signal indicates that the transducer head 124 under test has experienced pole tip protrusion. Specifically, because pole tip protrusion involves a physical change in the shape of the transducer head 124, the position of the head with respect to the center line of the track 136 will change. Accordingly, the position error signal derived from servo sector position bursts included

in the servo sector encountered by the transducer head 124 following the data sector to which the test sequence was written, will indicate a sudden change of position. Because pole tip protrusion is typically the result of heating of the transducer head 124 by a write current or write boost current that is too high for the ambient temperature of the disk drive 100, the detection of pole tip protrusion indicates a need to reduce the amount of write current and/or write current boost.

Following the detection of an error reading servo sector position data at step 704, or a sudden change in the position error signal at step 708, a determination is made as to whether the write current boost is set at a minimum value, in the present example level 0 (step 712). If the write current boost is at a minimum value, the write current i is set equal to $i - 1$, and the write current boost is set equal to a maximum value (step 716). If the write current boost is not equal to 0, the write current i is left at its present value (*i.e.*, i is set equal to i) and the write current boost j is set equal to $j - 1$ (step 720). The system then returns to step 700 to determine whether the changes have been sufficient to avoid the indicated problem.

If no error in reading servo sector position data and no abrupt change in the position error signal is detected, then the values for the write current and the write current boost used during the preceding test sequence (*i.e.* during the previous iteration of step 700) are validated, and may be used as the nominal values stored in the table of write currents and write current boosts (step 724).

With reference now to Fig. 8, steps followed to adjust the write current and/or write current boosts applied during a write operation based on the observed temperature

of the disk drive **100** are set forth. It should be noted that while the steps set forth in **Figs. 6 and 7** are generally performed during optimization of the disk drive **100** prior to delivery to the end user, the steps illustrated in **Fig. 8** are performed during normal operation of the disk drive **100**. For instance, the steps set forth in **Fig. 8** may be performed every minute for the first 15 minutes after the drive has been powered up, and every five minutes thereafter.

Initially, at step **800**, the temperature of the disk drive **100** is measured. Next, the temperature adjusted write current and/or write current boost is calculated (step **804**). At step **808**, the write operation is performed using the calculated write current and write current boost. Although the example illustrated in **Fig. 8** assumes that an algorithm is used to adjust the write current and write current boost for a nominal temperature to the observed temperature, such is not necessarily the case. For example, different write current and write current boosts can be stored for a variety of temperature ranges. According to such an embodiment, step **804** involves reading a write current and write current boost from a table.

The algorithm used to alter the write current and write current boost based on observed temperature is, according to one embodiment of the present invention, determined for each model or family of hard disk drives **100**. According to still another embodiment, a different algorithm for adjusting the write current and write current boost may be developed for disk drives **100** within a family of drives using transducer heads **124** supplied by each different vendor of transducer heads **124** that might be used in that particular disk drive **100**. As a further alternative, in particular where a table of write

current and write current boost levels containing entries for different temperature ranges is used, the variations in current levels may be developed for each individual disk drive 100.

In general, the determination of an appropriate algorithm for adjusting the write current and write current boost involves testing a disk drive 100 in the same manner as described above in connection with Figs. 6 and 7. However, instead of performing such testing at a single ambient temperature, the testing is performed at a variety of temperatures. In this way, a curve describing the performance of the disk drive 100 at various temperatures and for various write currents and write current boosts can be developed empirically. The algorithm used to alter a write current or write current boost for an individual drive should therefore be an algorithm adapted to follow the curve developed for the representative disk drive 100.

Furthermore, it should be appreciated that different algorithms may be used for different temperature ranges. For instance, a first algorithm may be used to adjust the write current and write current boost amounts at temperatures greater than a selected temperature. A second algorithm may then be used to adjust the amount of write current and write current boost at temperatures below the selected temperature. An example of an algorithm for use at high ambient temperatures is as follows:

$$\text{adjustment amount} = 5 - (\text{observed temperature} - 27)/5.$$

The resulting value is the number of digital to analog converter levels by which the write current amount is adjusted. An example of an algorithm used to adjust write current levels below a selected temperature is:

adjustment amount = $-(\text{measured temperature} - 55)/11$.

Again, the resulting value is the number of levels by which the nominal write current amount is adjusted. Similar algorithms may be used in connection with write current boost levels. The algorithm or algorithms may be implemented in firmware or microcode running on the controller 132. Memory for storing tables may be separately provided or included as part of some other component, such as the controller 132.

The foregoing discussion of the invention has been presented for purposes of illustration and description. Further, the description is not intended to limit the invention to the form disclosed herein. Consequently, variations and modifications commensurate with the above teachings, within the skill and knowledge of the relevant art, are within the scope of the present invention. The embodiments described hereinabove are further intended to explain the best mode presently known of practicing the invention and to enable others skilled in the art to utilize the invention in such or in other embodiments and with various modifications required by their particular application or use of the invention. It is intended that the appended claims be construed to include the alternative embodiments to the extent permitted by the prior art.